Jets and Tori in Proto-Planetary Nebulae: Observations vs. Theory

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Summary. We report on a study of the time sequence for the appearance of high-velocity jets and equatorial tori in the transition of stars from the asymptotic giant branch to the planetary nebulae phase. Jets and tori are prominent features of this evolution, but their origins are uncertain. Using the kinematics of molecular tori and molecular or optical jets, we determine the ejection histories for a sample of well-observed cases. We find that jets and tori develop nearly simultaneously. We also find evidence that jets appear slightly later than tori, with a typical jet-lag of a few hundred years. The reconstructed time-lines of this sequence provide good evidence that jets and tori are physically related, and they set new constraints on jet formation scenarios. Some scenarios are ruled out or rendered implausible, and others are challenged at a quantitative level.

Key words: stars: mass-loss, planetary nebulae: general, binaries

1 Introduction

Jets and equatorial tori are among the most prominent morphological features of proto-planetary nebulae (proto-PNe). They are also relatively common, but their origins are uncertain. In this paper we attempt to make connections between the observed characteristics of the jets and tori, and various theoretical ideas on how they might form.

The paper is divided into two parts. In the first part we focus on observations, and address the question whether jets and tori are related in some way. We examine this in the time domain, by asking if there is a consistent pattern for the ejections, and what the relevant time scales are. We conclude that jets and tori are related: they develop nearly simultaneously, and we find evidence for a torus-jet sequence. In the second part of the paper, we use this torus-jet relation to evaluate different formation scenarios. It favors and constrains certain scenarios, and rules out others.

2 Observations

The launching of high-velocity jets and the ejection of equatorial tori are among the most traumatic events in the lives of stars in the transition from the asymptotic giant branch (AGB) to the PN phase. Figure 1 illustrates the relatively sudden change in geometry from the regular AGB mass-loss. The left hand panel shows a simplified picture, and the right hand panel shows a real example, AFGL 618, imaged with the HST. The jets of AFGL 618 show multiple components (the cause is not known), but they have well defined tips, and there is a dense torus, seen in absorption around the equator, which was formed by the last major mass-loss event from the star. It might come as no surprise that such dramatic mass ejections are somehow related, but the question has not previously been addressed in any detail.

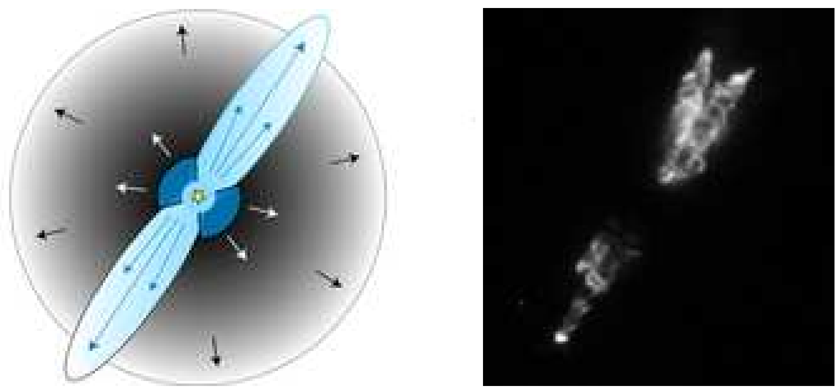

Fig. 1. Jets and tori: (**left**) simplified picture; (**right**) the proto-PN AFGL 618, imaged by the Hubble Space Telescope, adapted from [18]

2.1 Kinematic Ages

We explore the relation between jets and tori in the time domain by estimating when each component was ejected. We can determine the kinematic ages of the jets from their velocities and radial extent. This can be done using imaging and spectroscopy of optical emission lines or molecular lines if there are molecules in the jets. The estimates require information on the tilt of the system (because only projected quantities are measured), and in well studied cases this can be determined from geometrical or kinematic considerations. Observations of optical proper motions of the tips of the jets can also yield kinematic ages, independent of the tilt.

For the equatorial outflows, we emphasize in this study objects with massive molecular tori whose expansion velocity and radial extent have been observed in millimeter CO lines. This is an important consideration: tori can

of course be studied in optical emission lines in fully developed PNe, but by then the kinematics of the gas will have been strongly affected by the onset of ionization, and will no longer be a reliable indicator of the time since ejection. We note that the ejection of the tori in some cases may be more spherically symmetric than suggested in out schematic figure, but pierced by the jets: this does not appreciably affect our discussion. We also note that in the classic paper [16], Soker & Rappaport argued that tori are not distinct ejections, but are simply formed by jets snow-plowing the AGB wind towards the equatorial plane; however the high masses and high mass loss rates typically found, e.g., [6], argue for something different.

There are nine objects with observations suitable for comparing the kinematic ages of jets and tori. They range from AGB stars to young PNe: π^1 Gru, AFGL 618, V Hya, He 3-1475, M 2-56, M 1-92, M 2-9, M 1-16, KjPn 8. We have omitted a few well-observed cases where the geometry is complex, e.g., AFGL 2688 [3]. The data for the sample come from the work of several research groups and the details are given in [5] (see also J. Alcolea, this volume). For this sample, the median expansion velocity of the tori is $10\,\mathrm{km\,s^{-1}}$ (comparable to or less than the wind velocity near the end of the AGB), and the median jet velocity is $160\,\mathrm{km\,s^{-1}}$. The kinematic ages range from 50 to 5,000 yr, and they roughly correlate with the evolution of each object suggested by the morphology of the nebula and/or the temperature of the central star; this is consistent with all ejections occurring near the end of the AGB.

2.2 Jet-Lag

The kinematic ages of the jets are plotted against those of the tori in the left hand panel of Fig. 2. In spite of the relatively crude measures involved (especially of the tori which are not highly resolved) and the uncertainties in the orientations (see [5] for details), the ages are seen to be correlated. The jets and tori occur nearly simultaneously, strongly suggesting they are physically related.

Further inspection of the figure shows that the kinematic ages of the jets are slightly less than those of the tori. There is good evidence to suggest that the kinematic ages are quite reasonable estimates of the true travel times: for the tori because of their large inertia and low velocity, and for the jets because of the Hubble-like ballistic flows seen in well studied cases, e.g., [1, 2, 19]. On this basis, the most reasonable interpretation of the figure is that the jets typically develop after the tori, with a delay or jet-lag. From the age measurements for the ensemble of objects, the typical jet-lag is 300 yr.

Although there is good evidence for approximate, unimpeded ballistic motion for the jets, the dynamics is not understood in detail, so there could be slight variations. The difference between the true age and the kinematic age can be seen by writing the former as $t = \int dr/v(r)$ (where v is the velocity as a function of distance r), whereas the latter is r/v at the current epoch.

To the extent that the jets are decelerated by interaction with the circumstellar gas, their true ages will therefore be shorter than the kinematic ages, and the jet-lag will be longer than we estimate. Acceleration of the jets is unlikely to dominate the kinematics (see [5] for details), but the jet-lag could be somewhat shorter. In any event, our measurements refer to the tips of the jets and characteristic or average radii of the tori, so our finding that the jets are almost simultaneous or delayed relative to the tori is likely to be robust. This sequence is also consistent with the kinematics and morphology seen in individual cases, e.g., [6], where material of the torus is entrained along the sides of the jets.

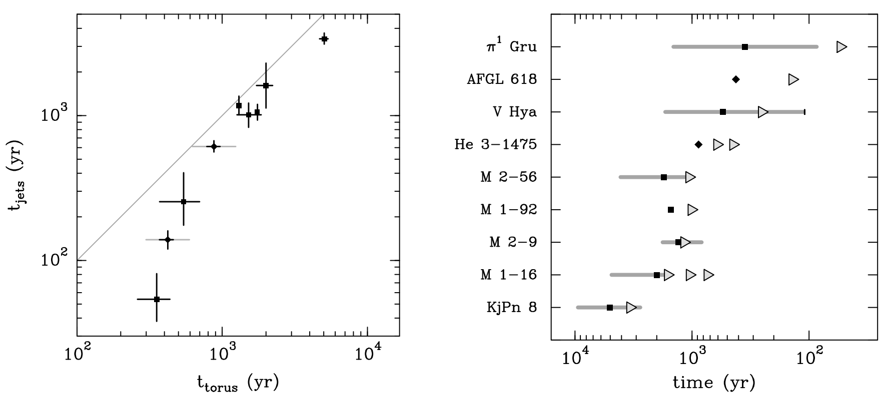

Fig. 2. The timing of jets and tori: (**left**) kinematic ages of jets vs. tori (error bars indicate uncertainties in inclinations, proper motions, etc., and the continuous line shows where the ages are equal); (**right**) reconstructed time lines, with time axis in years ago from now (horizontal lines denote the duration of torus ejections, and arrowheads denote jet ejections)

2.3 Torus-Jet Sequence

Using our timing estimates we can reconstruct the evolution of the outflows, and this is shown in the right hand panel of Fig. 2. The horizontal axis is time in the past, measured from the current epoch. The filled points show when the tori were ejected, and the horizontal lines show estimates for the duration of the ejection, based on the radial widths of the tori and the expansion velocity. These would be overestimates if there is an appreciable internal dispersion in the gas. The arrowheads show when the jets were launched. In two cases there are data for multiple jets, and the interval between them is seen to be comparable with the jet-lag.

In spite of the considerable heterogeneity of the data used to make Fig. 1, the overall picture for the ensemble of objects is remarkably consistent. Tori

are ejected on relatively short time scales, and jets are launched at the same time or shortly after.

3 Implications

We now turn to the implications of these results for ideas on jet formation. There are several theoretical ingredients, MHD launching and collimation, disks of various kinds (primary, secondary, circum-binary), the effects of a common envelope phase, etc., and they come together in four types of scenario which we discuss in turn.

3.1 Scenarios

Each scenario has fairly specific predictions on the relations between the jets and tori which we can test using the findings from the observations described in the previous section.

Single Stars

The first scenario involves magnetic winds from single stars. Current models with a strong enough magnetic field can produce jets [4] although there are likely problems with this idea [17]. In the context of our present results, it is unclear if single star models can produce sudden jets, and those available do not produce co-ordinated tori. The equatorial density enhancements in the simulations by [4] are input separately, and do not constitute a discrete ejection. In view of the close connection between jets and tori found here, the current single star models do not give a good description of the observations.

Disks around Binary Companions

The second scenario involves the launching of jets from accretion disks around binary companions, e.g., [10, 16], similar to the jet launching picture in young stellar objects. In this case the disk is fed by the mass-loss from the AGB primary. This scenario has several attractive features. First, it provides a natural mechanism for enhanced mass-loss in the equatorial plane. Second, it provides a causal and sequential relation between the torus and jets, because the enhanced mass-loss of the torus feeds the accretion disk that in turn fuels or triggers the jets. It even provides a natural explanation for jet-lag.

Jets will not immediately respond to enhanced mass-loss and enhanced accretion, but will lag by the time it takes the matter to spiral into the companion. This accretion time is the viscous timescale of the disk, which is given by the following expression in the usual α-prescription:

$$t_\nu = 160\,\mathrm{yr}\left(\frac{\alpha}{0.1}\right)^{-1}\left(\frac{R}{1\,\mathrm{AU}}\right)^{3/2}\left(\frac{M_2}{1\,M_\odot}\right)^{-1/2}\left(\frac{H/R}{0.1}\right)^{-2}, \tag{1}$$

where α is the viscosity parameter, M_2 is the mass of the companion, and H and R are the scale height and radius of the disk, respectively. For reasonable values of the parameters (given by the scaling values in the equation), the viscous timescale is a few hundred years, comparable with the typical jet-lag found from the observations. Thus the jet-lag could well be the signature for the presence of an accretion disk (which is not otherwise detected) and can provide quantitative information on its properties.

In spite of the success of this scenario, one feature that is not generally explained is the onset of a discrete torus. It may be connected with spin-up by the secondary, and/or a critical envelope mass of the primary. This point warrants further study.

Spun-up Envelopes

The third type of scenario involves the effects of spin-up of the envelopes, e.g., [11, 8], especially during a common envelope phase which might naturally lead to ejection in the equatorial plane. One version involves common-envelope ejection to form a torus, while the spin-up of the envelope generates jets. A second version involves the build-up of the stellar magnetic field by rotational shear until it explodes in both the polar and equatorial directions. This case is interesting in view of the possible observable characteristics of the magnetic field in the tori, e.g., [7, 13].

For both of these scenarios, the time scale for the sequence is likely to be fairly rapid, so it is unclear if either of them is consistent with jet-lag of a few hundred years. Similarly, it is unclear whether common-envelope ejection or a magnetic explosion can give rise to the low velocity tori: in all observed cases the bulk of the mass comes off with a velocity comparable to or lower than the wind velocity on the AGB. Realistic simulations of the ejection process in a common envelope need to be developed.

A hybrid model, in which a binary companion first accretes matter and blows jets, and is then engulfed by the primary to form a common envelope phase that ejects a torus is ruled out: it gives the wrong torus-jet sequence.

Disks around the Primary Core

The fourth type of scenario involves the production of jets from an accretion disk around the primary core or core-remnant [14, 15, 12, 11]. One version involves a low mass object that is engulfed by the primary and is tidally disrupted to form a disk-jet system around the core, to be later followed by the normal evolution of the star and the ejection of the nebula. This scenario can be ruled out because the jets and torus are uncoordinated (contrary to observations) and they occur in the wrong sequence.

A second possibility is for a companion to eject a torus in a common envelope phase, followed by tidal disruption forming a disk-jet system around the core. This generates the correct torus-jet sequence, but is likely restricted to a narrow range of companion mass, and the time scales are uncertain.

A third possibility is one in which a torus is formed by common envelope ejection, and then the secondary undergoes Roche lobe overflow, feeding a disk-jet system around the remnant core. This gives the correct torus-jet sequence, but the time scale on which the disk is formed is likely too long, and it can probably be ruled out.

3.2 Summary of Scenarios

As seen by the above discussion, the torus-jet connection provides important constraints on possible scenarios. Table 1 provides a summary, with a rating for each of the cases considered. Half of them are ruled out or made implausible, and the remainder need more realistic simulation for comparison with the observed constraints.

All the plausible scenarios involve a stellar or sub-stellar mass companion. Given the ubiquity of jets, this would imply interactions on the AGB should be a common phenomenon, and there is growing evidence that this might be the case, e.g., [9] (see also R. Sahai, this volume).

Table 1. Jet-Torus Scenarios

Scenario	Rating	Comments
mag. wind from single star	−	jets *and* torus?
primary mass loss + companion acc. disk	+	discrete torus ejection?
companion acc. disk + CE ejection	−	wrong sequence
CE ejection + mag. polar wind	+	jet-lag?
(CE) mag. polar & equatorial explosion	+	jet-lag?
(CE) primary acc. disk + late PN	−	wrong sequence
CE ejection + primary acc. disk	+	jet-lag?
CE ejection + RLOF	−	time scale too long?

4 Conclusions

The results of this study show that the launching of jets and the ejection of equatorial tori are related. They are nearly simultaneous, and there is evidence for a torus-jet sequence with a typical delay time or jet-lag of a few hundred years.

The near simultaneity of the outflows, the torus-jet sequence, and time scales for their development set interesting constraints on scenarios for jet and torus formation. The observations already rule out or make implausible several proposed scenarios, and for others they pose well defined, quantitative questions that need to be addresses by realistic simulations.

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